

A New Look at Foam for Unloading Gas Wells

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by

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Abstract

When initially completed, many natural gas wells are capable of blowing water and hydrocarbon liquids to the surface. But, with depletion of the reservoir pressure, there comes a time when liquids can no longer be lifted to the surface by the flowing gas and they begin to accumulate in the bottom of the well, dramatically inhibiting or stopping gas production. A frequently applied treatment for such wells is addition of surfactants to the well stream. With surfactants, foams can form that can enhance capacity for lifting liquids. Although widely used, the effects of surfactants on flow regimes and correlations for predicting their performance are not available.

The objectives of this project were to collect pressure drop and flow rate data for foam flow in vertical tubing, to compare these data to available correlations for gas-liquid flow, and to develop a new correlation for foam flow based on the Duns-Ros model. Listed below are three tasks specific to these objectives. A fourth task of general interest for technology transfer and a fifth task that completes a previous SWC project are also included.

Task 1: Pressure Drop and Flow Rate. Use the existing flow loop in the High Bay Lab at CSM to experimentally study this relationship for conditions typical of stripper gas wells.

Task 2: Existing Correlations. Compare existing correlations with results of Task 1.

Task 3: New Correlation. Modify the Duns-Ros correlation to fit the foam flow data of Task 1.

Task 4: Liquid-Lifting Short Course. Organize a one-day short course on lifting liquids from gas wells using the CSM Flow Loop for hands-on demonstrations.

Task 5: Final Development and Testing of Mist Device. Complete the development of a mist generator suitable for testing in a shallow gas well.

Accomplishments for each of these tasks are summarized below.

Task 1: Pressure Drop and Flow Rate. Pressure drops were measured for gas flow rates from just below the critical flow rate to well above that rate. In future work, pressure drop measurements for foaming systems need to be extended to lower gas flow rates. Measured critical flow rates for foam varied from about one-third of the rate for water up to the same rate as water, depending on the test method used.

Task 2: Existing Correlations. The Duns-Ros correlation was found to agree with the measured pressure drops for tests with surfactant. For liquid rates above 4 bbl/day, the Gray correlation also fit measured pressure drops.

Task 3: New Correlation. A new correlation was not developed because of the success of the Duns-Ros correlation.

Task 4: Liquid-Lifting Short Course. Two short courses (one in March 2005 and one in October 2005) were held with about 10 participants in each course. In addition, arrangements were made to provide a short course for the 2006 Gas Well De-Liquification Workshop to be held in Denver on February 27 to March 1 of 2006.

Task 5: Final Development and Testing of Mist Device. The plan for this device specifies two main parts: an electrical power converter to provide the driving voltage for the ultrasonic device, and the ultrasonic device itself. The first part was completed; funding from a corporation has been obtained to pay for completion of the device in 2006.

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Introduction

Removal of water and hydrocarbon liquids from gas wells is increasingly recognized as an important topic for mature gas reservoirs. Foam, produced by surfactants, is one of the leading methods for unloading gas wells. The surfactants are delivered to the well as soap sticks or as liquid injected into the casing-tubing annulus or down a capillary line to the producing interval. Although the relation between pressure drop and flow rate has been studied previously, there are questions about the most appropriate method for estimating pressure profiles. The objective of this research is to re-visit the relationship and determine if existing correlations are adequate.

In the following section, the approaches used for the five tasks this project are summarized. Then, the results of the five tasks are presented, followed by conclusions and references.

Description of Approaches

Task 1: Pressure Drop and Flow Rate. An existing flow loop in the High Bay Lab in the Petroleum Engineering Department at the Colorado School of Mines was used to experimentally study the relationship between pressure drop and flow rate for foam flow.

The layout of the flow loop is shown in Figure 1. In brief, gas from the blower mixes with recycle liquid at the bottom of the loop, then the combined stream travels up inside the vertical test section, from which it is re-circulated to the gas-liquid separator. At the gas-liquid separator, the gas exits up to the blower, and the liquid exits down to the recycle pump. The vertical test section and portions of the recirculation lines are made of transparent PVC pipe to allow visual assessment of flow. The flow loop operates near ambient pressure and temperature.

For the foam tests, the vertical test section consisted of a 2-inch ID PVC pipe that extended 40 feet from the floor to the ceiling of the High Bay Lab. For measuring the pressure drop, two pressure taps were placed at each end of a 20-foot-tall test section in the middle of the 40-foot span. At each end of the test section, a remote-controlled ball valve was installed so that we could measure the liquid holdup in the test section. These valves could be opened or closed by switching a valve on a compressed-air line. In the open position, the ID of each ball valve is 2 inches – the same as the PVC pipe.

After preliminary testing, we found that separation of gas and liquid water in the produced foam with the separator presented new challenges. We enlarged the separator to foster better separation of gas and liquid, but even that was insufficient for all tests. Thus it became necessary to re-circulate foam in some tests without complete separation. To measure the liquid portion of the re-circulating foam, we added a mass balance that weighs the flexible line that conveys foam from the pump to the bottom of the flow loop.

Two different methods were used to study flow of foam. In the first method (Constant-Rate Method), water with and without surfactant was circulated at a constant rate while gas rates were varied from high rates (well above the critical rate) to lower rates. The gas flow rate was decreased in steps until liquid loading occurred. This method provides one objective indication of critical flow rate.

In the second method (Fixed-Charge Method), 1 to 3 liters of water (with and without surfactants) were charged to the bottom of the flow loop. Gas rate was increased and the rate of water production from the loop was measured.

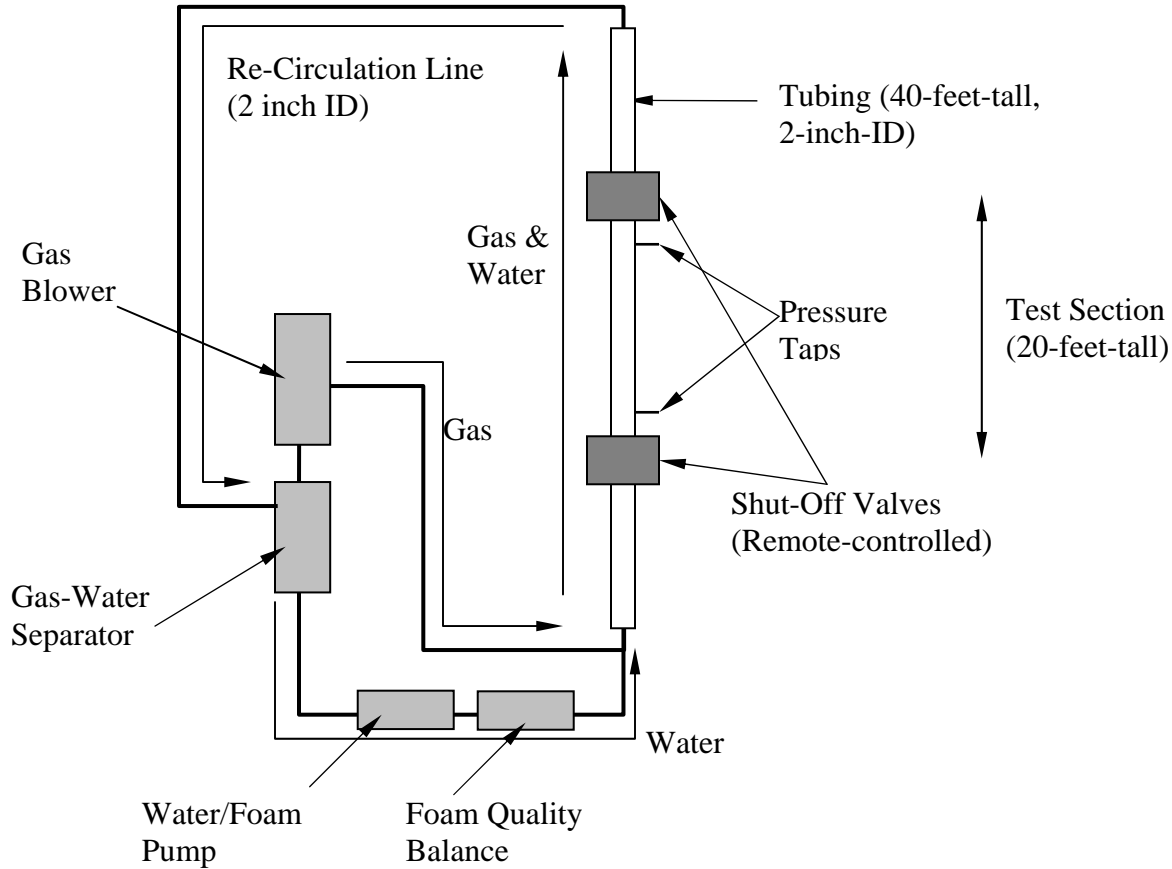


Figure 1. Schematic of Flow Loop.

Task 2: Existing Correlations. Two two-phase flow correlations were selected for this task: the Duns-Ros, and the Gray correlations. These correlations are summarized in Chapter 4 of Brill and Mukherjee (1999).

These correlations were chosen because they are well known and documented in the literature. The Gray correlation is frequently used for modeling performance of gas wells. Although the Duns-Ros correlation is not as popular, it was developed originally to fit a large set of laboratory observations; thus, it may be more appropriate for comparison to laboratory measurements of pressure drops.

Task 3: New Correlation. The objective for this task is to modify the Duns-Ros and the Gray correlations to fit the foam flow data of Task 1.

Task 4: Liquid-Lifting Short Course. The intent of this short course is to provide a new opportunity for learning about multi-phase flow based on a broad set of demonstrations with the

flow loop. I have provided small demonstrations to many visitors to the flow loop lab; this short course is an outgrowth of those experiences. I did not have to modify the loop in any significant way to present the short courses.

Task 5: Final Development and Testing of Mist Device. The intent of the mist device is to convert bulk liquid water into small droplets that can be easily lifted from the well. With previous support of the Stripper Well Consortium, the basic idea for this device was developed and tested in the flow loop. The final step is to build a device that can be tested in an actual well.

The mist device uses an ultrasonic approach for breaking the liquid into very small droplets. As shown in Figure 2, the size of droplets is inversely related to the frequency of vibration. Droplets of diameter larger than 100 microns cannot be lifted very far based on tests in the flow loop. On the other hand, droplets less than 10 microns in diameter are easily lifted.

The approach for this task is to work with an electronics specialist who has a lot of experience with down-hole electronics and acoustic devices. In short, this task was out-sourced.

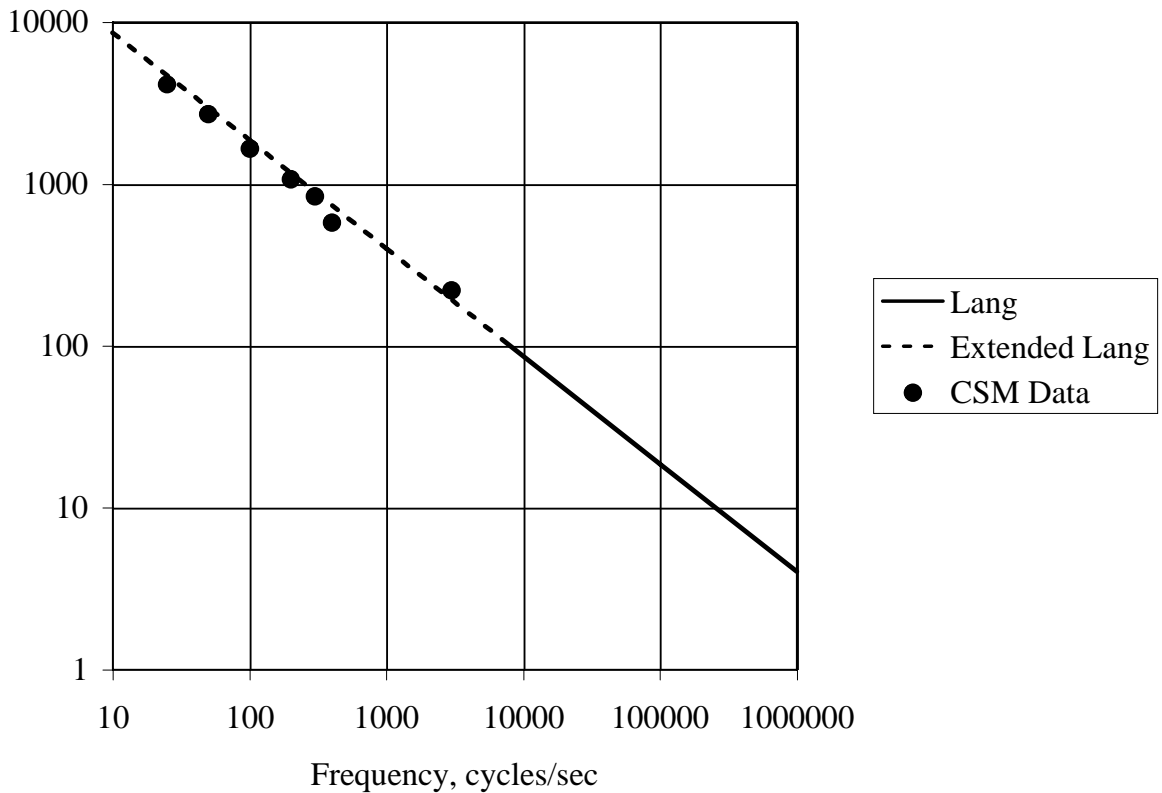


Figure 2. Correlation of size of droplet produced by vibrating water surface.

Results and Discussion

Task 1: Pressure Drop and Flow Rate. Before discussing pressure drop and flow rate observations, measurements of critical flow rates with and without surfactants are presented. These results were obtained with the Constant-Rate Method of operation for the flow loop. Results of tests at a liquid rate of 440 ml/min are compared in Figures 3 and 4, without and with surfactant. In the Constant-Rate Method, water injection rate is kept constant while electrical power to the blower is decreased in steps – the figures show results for each of six power levels. At each power level, the gas flow rate settles to a level consistent with the liquid flow rate and the pressure drop applied by the blower. When the gas flow rate is insufficient to lift liquids from the loop, the gas flow rate rapidly diminishes toward zero. The last rate for which stable flow is achieved is the critical flow rate.

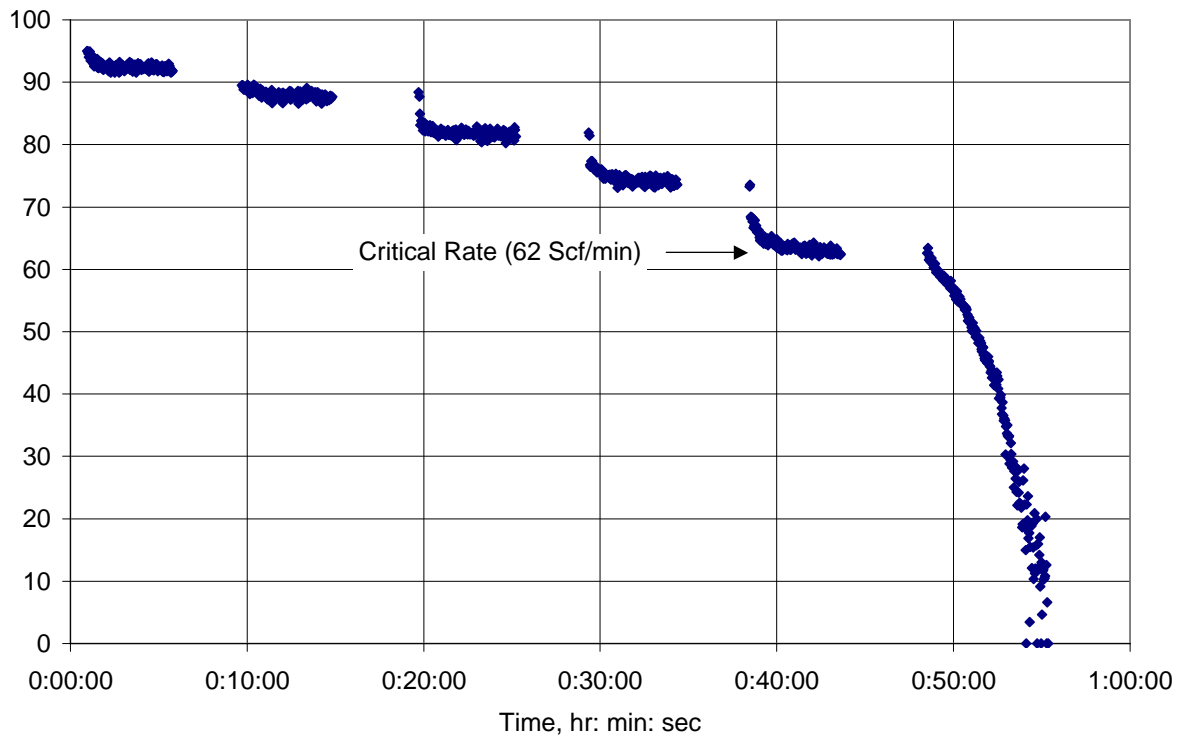


Figure 3. Example of critical flow rate observation for water with Constant-Rate Method. The liquid flow rate is fixed at 440 ml/min (equivalent to 4.0 Bbl/day).

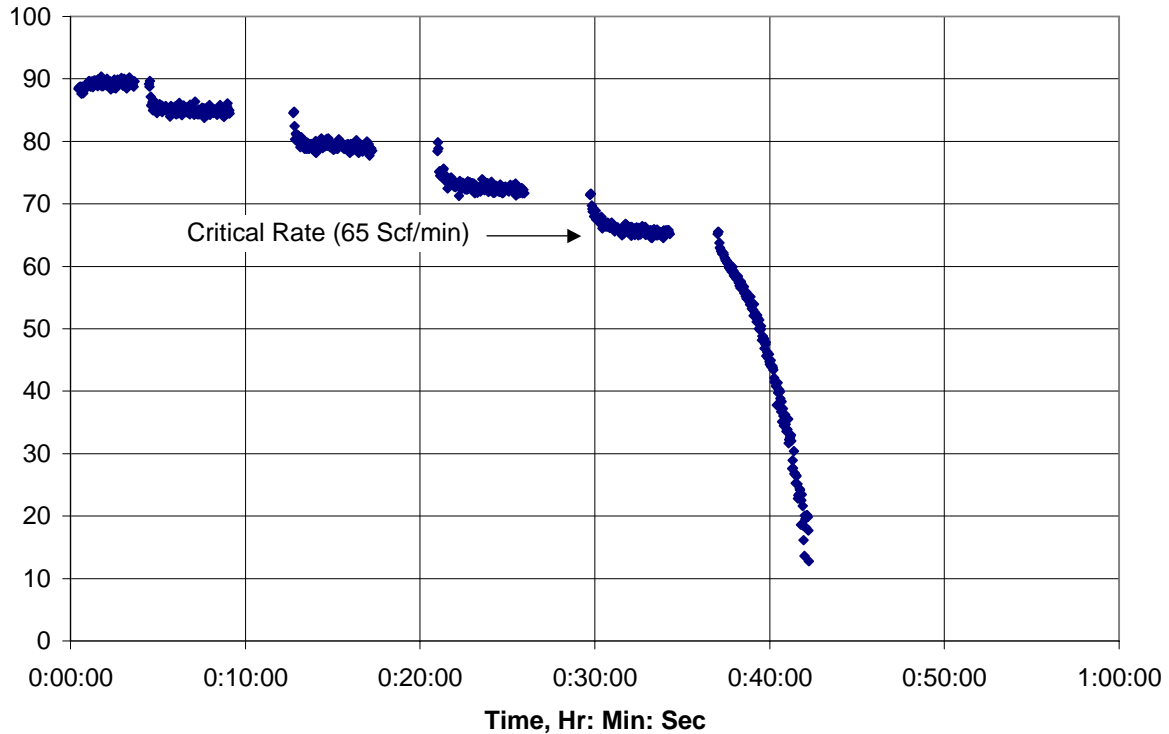


Figure 4. Example of critical flow rate observation for water with 0.05% surfactant (Champion Foamatron VDF-127) with Constant-Rate Method. The liquid flow rate is fixed at 440 ml/min (equivalent to 4.0 Bbl/day).

A set of critical flow rates for water and water with 0.05% surfactant are compared in Table 1. For low liquid flow rates, the observed critical velocity is greater for water with surfactant. At the highest water flow rate, the critical flow rate with surfactant is less. A similar trend was seen in two separate tests. In future work, critical flow rates with and without surfactant should be measured at higher flow rates.

Table 1. Critical flow rates measured with Constant-Rate Method in laboratory units (see Table 2 for field units).

Liquid Rate, ml/min	Critical Flow Rate, scf/min	
	Water	Water with 0.05% Surfactant (Champion Foamatron VDF-127)
110	67	72
220	61	67
440	62	65
880	61	56

Table 2. Critical flow rates of Table 1 converted to field units.

Liquid Rate, Bbl/Day	Critical Flow Rate, Mcf/day	
	Water	Water with 0.05% Surfactant (Champion Foamatron VDF-127)
1.0	96	104
2.0	88	96
4.0	89	94
8.0	88	81

Another perspective on lifting of water with surfactants was obtained with flow loop tests that used the Fixed-Charge Method in which a specific volume of liquid is charged to the bottom of the flow loop, and the liquid lifting response is observed as gas flow rate is increased. Results for some of these tests are shown in Figure 5. In that figure, the height of the “stagnant” water film is measured as a function of gas flow rate. In this case, stagnant refers to little or no net upward movement of liquid in the film; the appearance of the film is somewhat agitated, even boiling. We have observed this stagnant water film in many of our tests. For 1 liter of water with and without surfactant, the film heights converge at 40 feet. The line for 2 liters of water without surfactant converges with the line for 1 liter of water with surfactant. However, for 2 liters of water with 0.05% surfactant, the film height grows to 40 feet at a much lower gas flow rate.

The results for Constant-Rate tests (summarized in Table 1) and Fixed-Charge tests (in Figure 5) point to the same trend: critical flow rate performance of foam depends on the amount of liquid in the flow loop.

Another feature of Figure 5 is worth noting: the gas flow rate for which the height of the stagnant annular film reaches 40 feet should be close to the critical flow rate. Indeed, the film height should asymptotically grow as the flow rate increases. The asymptote should be the critical flow rate. Of the four curves in Figure 5, the curve for 2 liters of water with surfactant demonstrates the most asymptotic behavior, with an asymptote likely between 20 and 30 scf/min. The asymptotes for the other three curves are not clear, but they are greater than 45 scf/min.

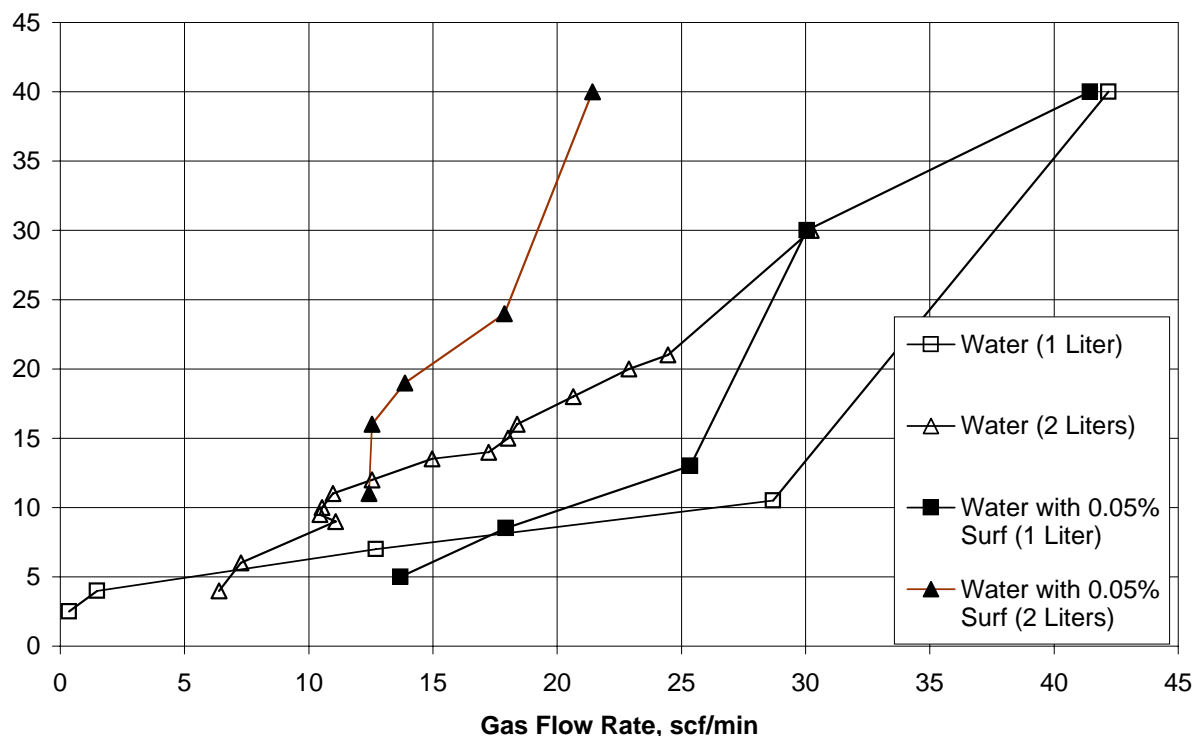


Figure 5. Results for flow loop tests with the Fixed-Charge Method using water with and without 0.05% surfactant (Champion Foamatron VDF-127).

Pressure drops over a 20-foot-long section of the flow loop were measured during the Constant-Rate tests. Pressure drops with and without surfactant (Champion Foamatron VDF-127) are compared in Figures 6 to 8. Liquid hold-ups (fraction of pipe volume that is occupied by liquid) are compared in Figures 9 to 11.

The pressure drops in Figures 6 to 8 show some interesting trends. First, all of the trends have a minimum pressure drop. This is consistent with the generally accepted notion that the pressure drop is dominated by two terms: a gravity term that decreases with increasing gas flow rate; and a friction term that increases with increasing gas flow rate. Second, the pressure drop increases with increasing liquid flow rate. And third, the pressure drops with surfactant are all slightly greater than the pressure drops without surfactant. Lea *et al.* (2003) show a similar trend in their Figure 8-1. There, the pressure drop with surfactant is below the pressure drop without surfactant at low rates; but at high rates, the pressure drop with surfactant is higher.

The hold-up figures also show interesting trends. In all cases, the hold-ups are less than 5% and decrease with increasing gas flow rate. Hold-up was not measured for liquid rate of 220 ml/min; but for 440 ml/min, the hold-up with surfactant was greater than without surfactant; and for 880 ml/min, the hold-ups with and without surfactant are about the same.

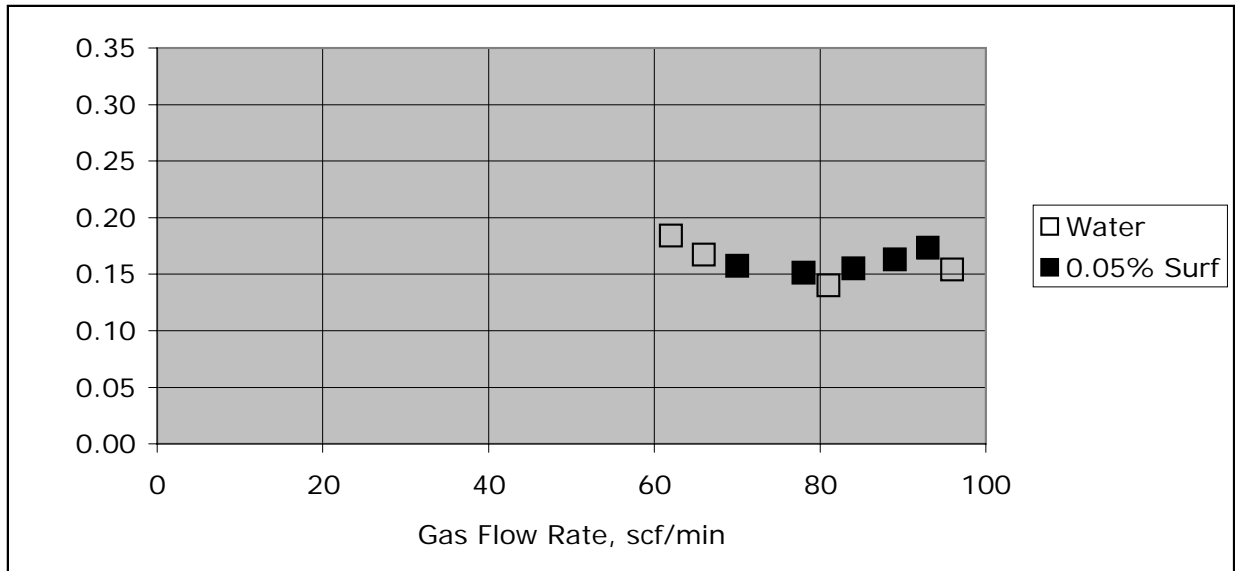


Figure 6. Pressure drop comparison for liquid rate of 220 ml/min.

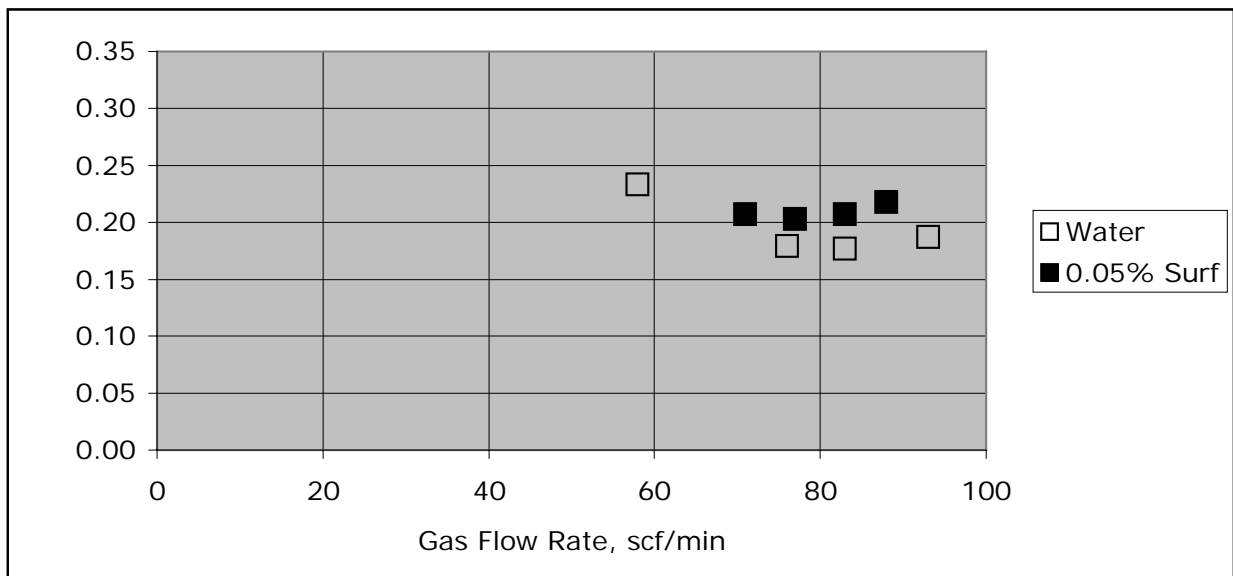


Figure 7. Pressure drop comparison for liquid rate of 440 ml/min.

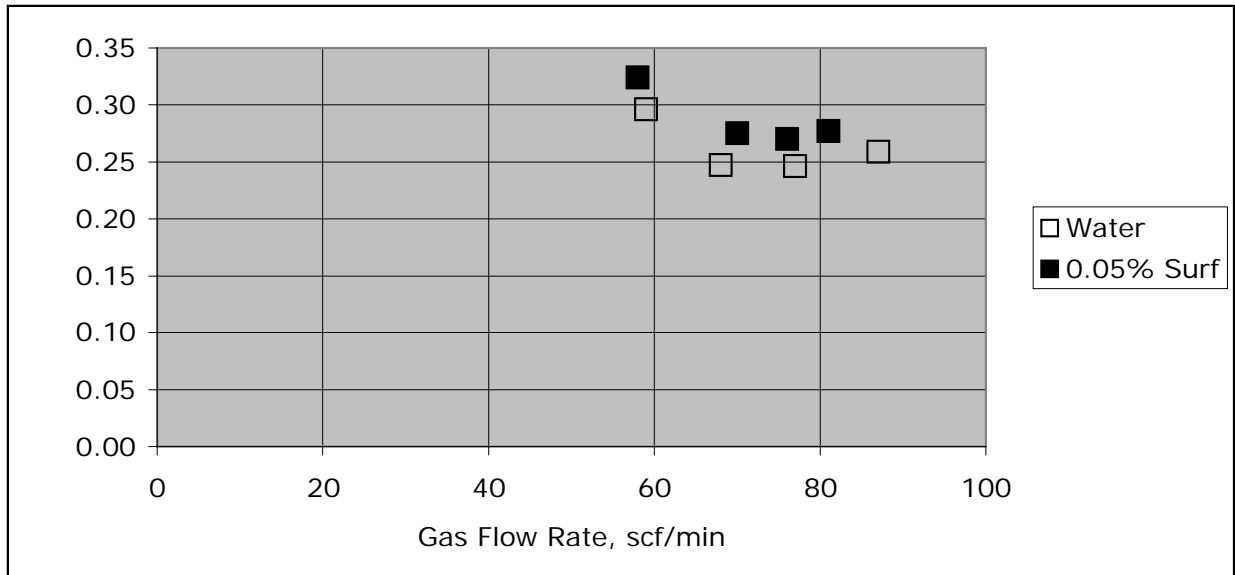


Figure 8. Pressure drop comparison for liquid rate of 880 ml/min.

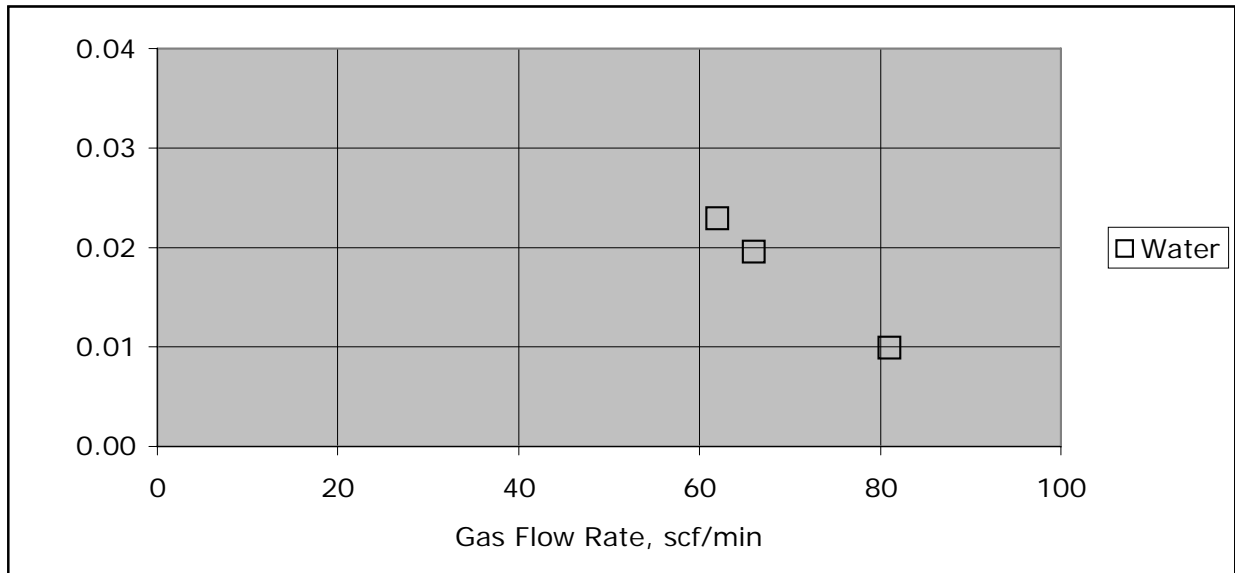


Figure 9. Hold-up for liquid rate of 220 ml/min.

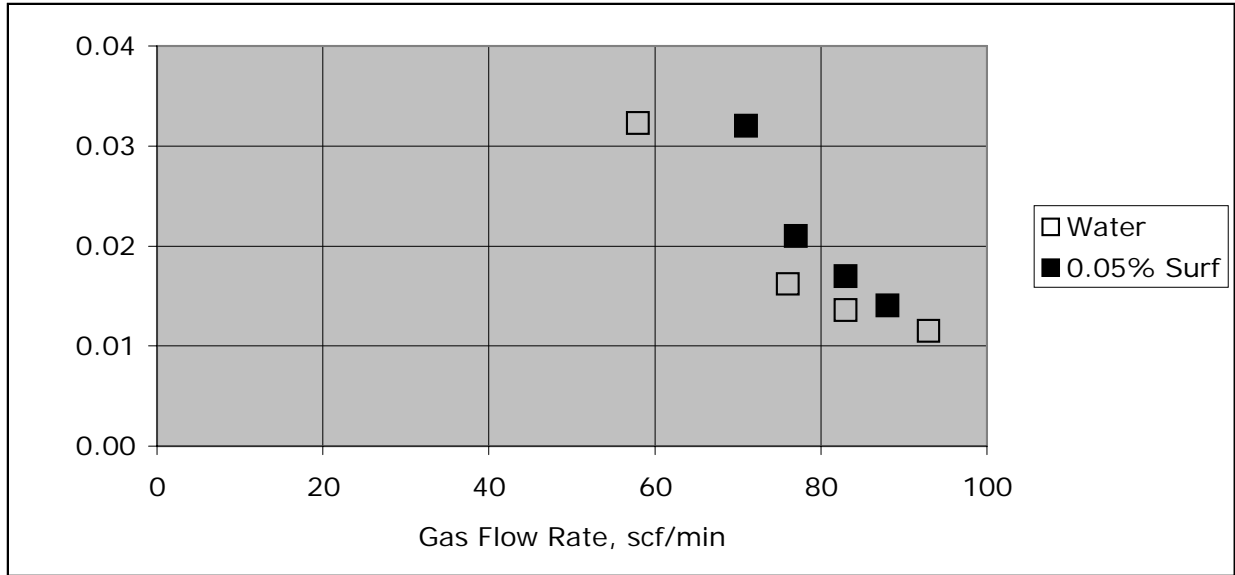


Figure 10. Hold-up comparison for liquid rate of 440 ml/min.

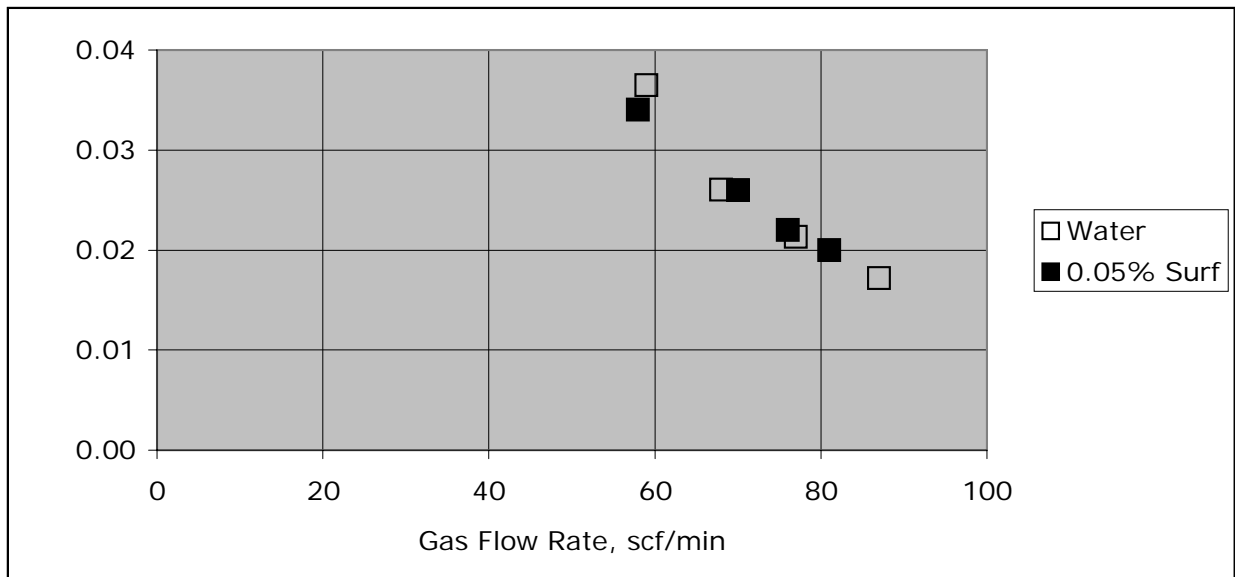


Figure 11. Hold-up comparison for liquid rate of 880 ml/min.

Task 2: Existing Correlations. The original objective of this study was to compare pressure drop and flow rate data for foam flow with correlations like the Hagedorn-Brown and the Duns-Ros models for two-phase flow in vertical pipes. Before considering those issues, comparisons of the observed critical flow rates with the 1969 Turner-Hubbard-Dukler (THD) correlation are in order. The THD critical flow rate is expressed as follows:

$$v_c = 0.68 \left[\frac{(\rho_l - \rho_g) \sigma_{gl}}{\rho_g^2} \right]^{1/4} \quad (1)$$

with the following units:

$$\begin{aligned} v_c &= \text{critical velocity, ft/s} \\ \rho_l, \rho_g &= \text{liquid and gas densities, g/cm}^3 \\ \sigma_{gl} &= \text{gas-liquid surface tension, dyne/cm} \end{aligned}$$

Or, in other units,

$$v_c = 1.91 \left[\frac{(\rho_l - \rho_g) \sigma_{gl}}{\rho_g^2} \right]^{1/4} \quad (2)$$

with

$$\begin{aligned} v_c &= \text{critical velocity, ft/s} \\ \rho_l, \rho_g &= \text{liquid and gas densities, lb/ft}^3 \\ \sigma_{gl} &= \text{gas-liquid surface tension, dyne/cm} \end{aligned}$$

Both versions of the THD correlation (Eqs. 1 and 2) state that the critical velocity should decrease as the gas-liquid surface tension decreases. Measurements show that the surface tension with the surfactant (Champion Foamatron VDF-127) is about 35 dynes/cm at 0.05% concentration, which is about one-half the value for water (70 dynes/cm) at room conditions. As a result, the critical flow rate with the surfactant should be about 84% of the value for water without surfactant. The data of Tables 1 and 2 do not support this expectation in general. Instead, the critical flow rate with surfactant can be above or below the critical rate without surfactants, depending on the liquid flow rate. This discrepancy may reflect failure of the constant-rate approach for measuring critical flow rates for surfactant solutions. The asymptotic behavior of the height of the annular film as described in Figure 5 and associated text indicates that the critical flow rate for surfactant solutions should be less than straight water.

Measured pressure drop and hold-up for tests with plain water are compared with the Duns-Ros correlation in Figures 12 and 13. The liquid rates for these tests were not fixed; the liquid rates for each gas rate are listed in Table 3. The gravity and friction components of the Duns-Ros correlation are shown in Figure 12. The Duns-Ros pressure drop is almost 50% greater than the measured pressure drop. The Duns-Ros hold-up in Figure 13 is a small fraction of the measured hold-up. This is not surprising because the Duns-Ros correlation predicts very small hold-ups for the annular mist flow regime, which is the dominant flow regime for the results of Figure 13.

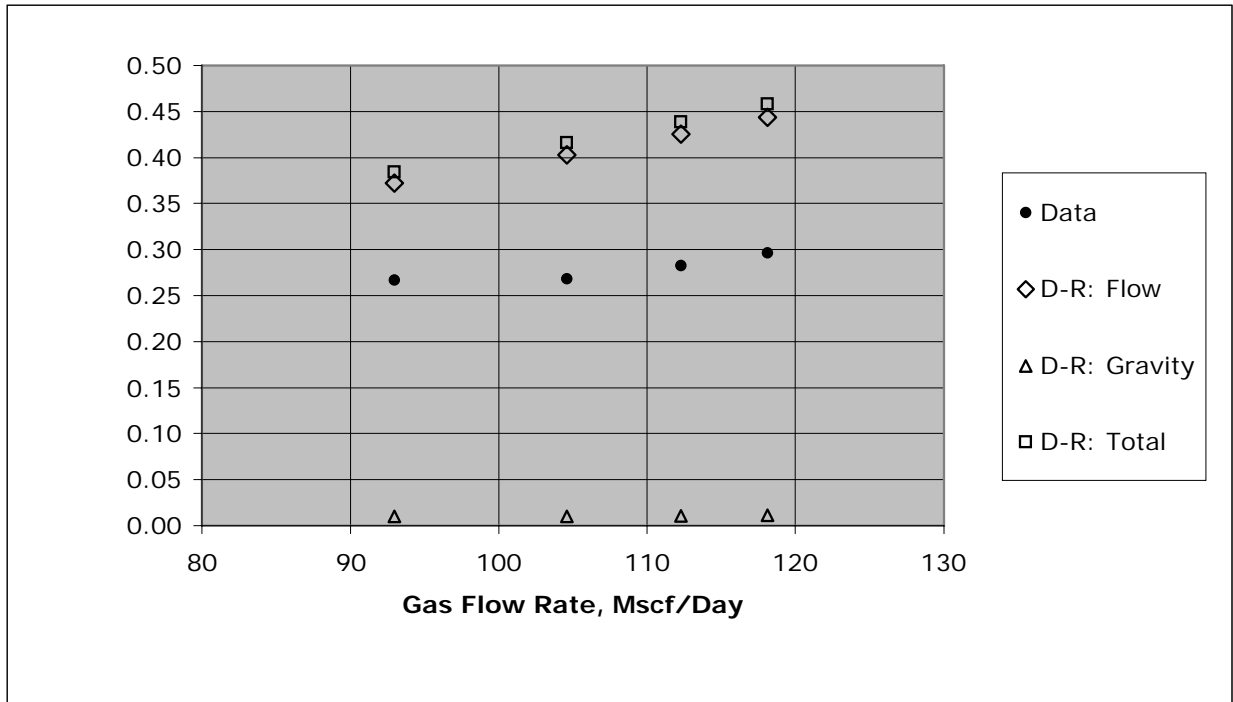


Figure 12. Measured and Duns-Ros pressure drops for plain water. See Table 3 for associated water flow rates.

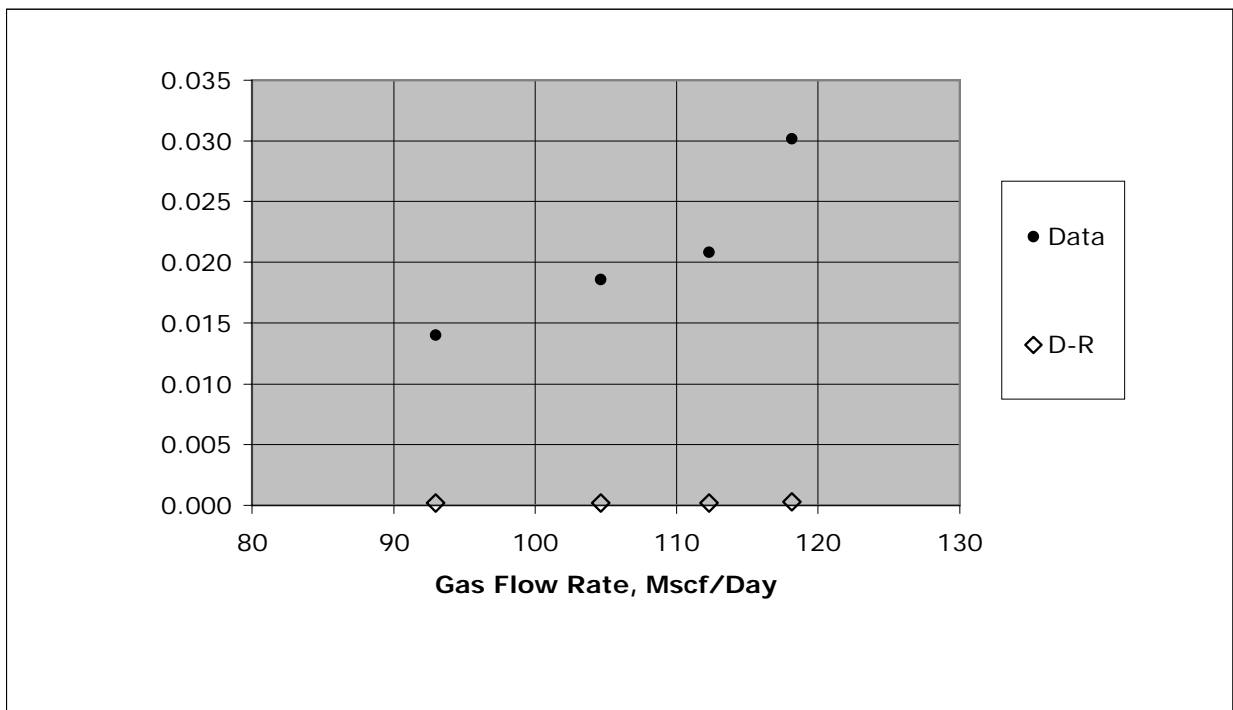


Figure 13. Measured and Duns-Ros hold-ups for plain water. See Table 3 for associated water flow rates.

Table 3. Gas rates and liquid circulation rates for the results shown in Figures 12 and 13 for tap water.

Gas Flow Rate, scf/min	Liquid Circulation Rate, ml/min
65	391
73	520
78	582
82	844
85	994

Measured pressure drop and hold-up for tests with 0.025% Baker-Petrolite surfactant in tap water are compared with the Duns-Ros correlation in Figures 14 and 15. The liquid rates for these tests also were not fixed; the liquid rates for each gas rate are listed in Table 4. The gravity and friction components of the Duns-Ros correlation are shown in Figure 14. For this set of results, the Duns-Ros pressure drop is within 10% of the measured pressure drops. The Duns-Ros hold-up in Figure 14 is a small fraction of the measured hold-up.

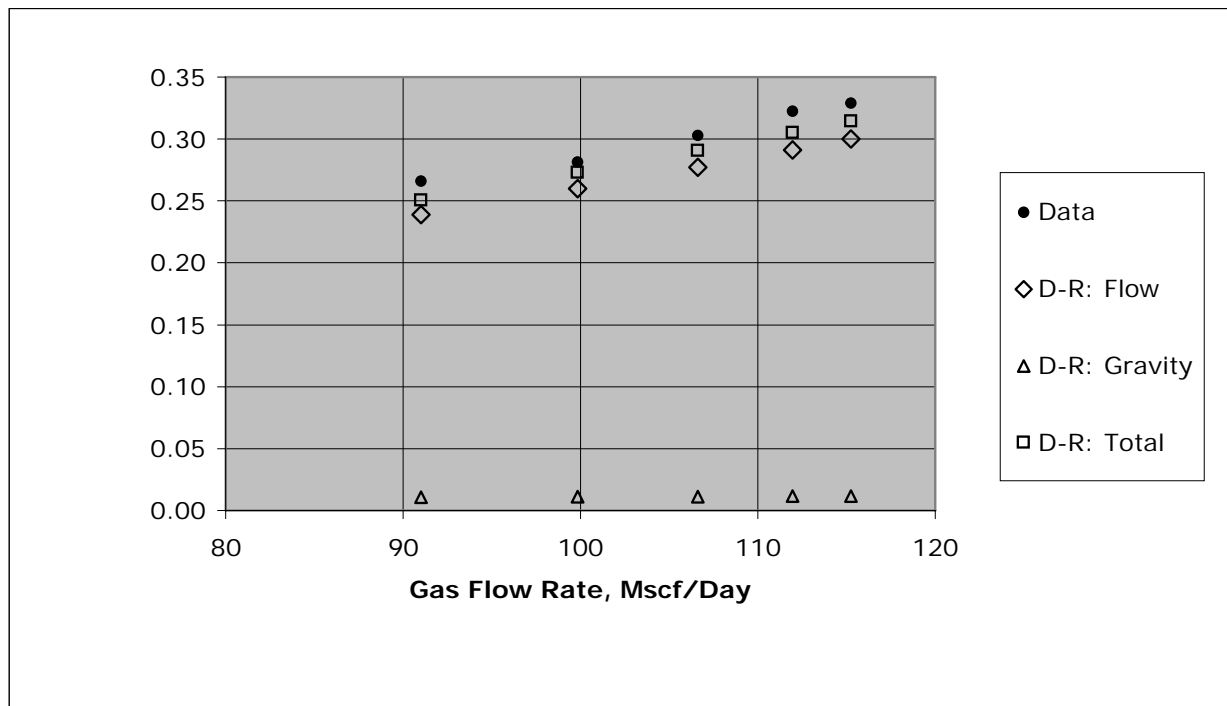


Figure 14. Measured and Duns-Ros pressure drops for plain water. See Table 4 for associated water flow rates.

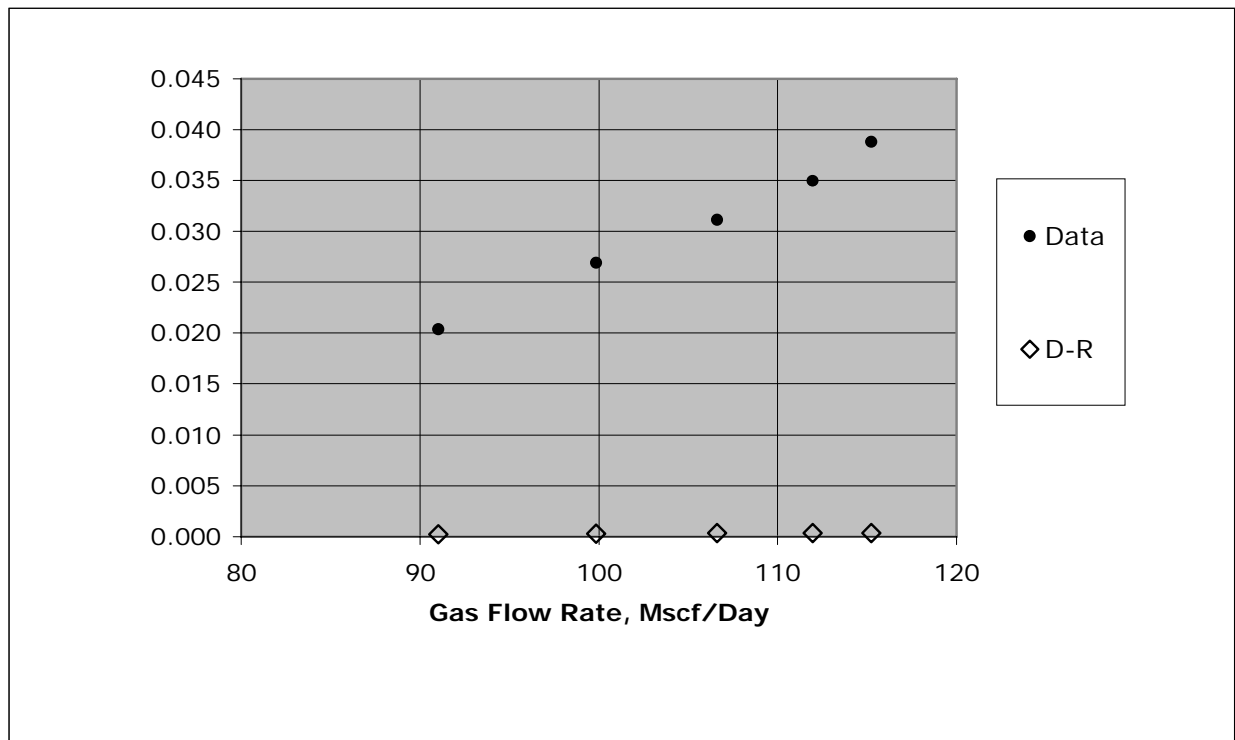


Figure 15. Measured and Duns-Ros hold-ups for plain water. See Table 4 for associated water flow rates.

Table 4. Gas rates and liquid circulation rates for the results shown in Figures 14 and 15 for Baker Petrolite surfactant in tap water.

Gas Flow Rate, scf/min	Liquid Circulation Rate, ml/min
63	569
69	751
74	869
78	977
80	1085

Some similar trends were observed for a second set of flow tests with Champion Foamatron VDF-127. The results of these tests are compared with the Gray correlation in Figures 16 to 21. The Gray correlation predicts much higher pressure drop than was observed for water. But for tests with surfactant, the Gray is closer, especially at the highest liquid flow rate.

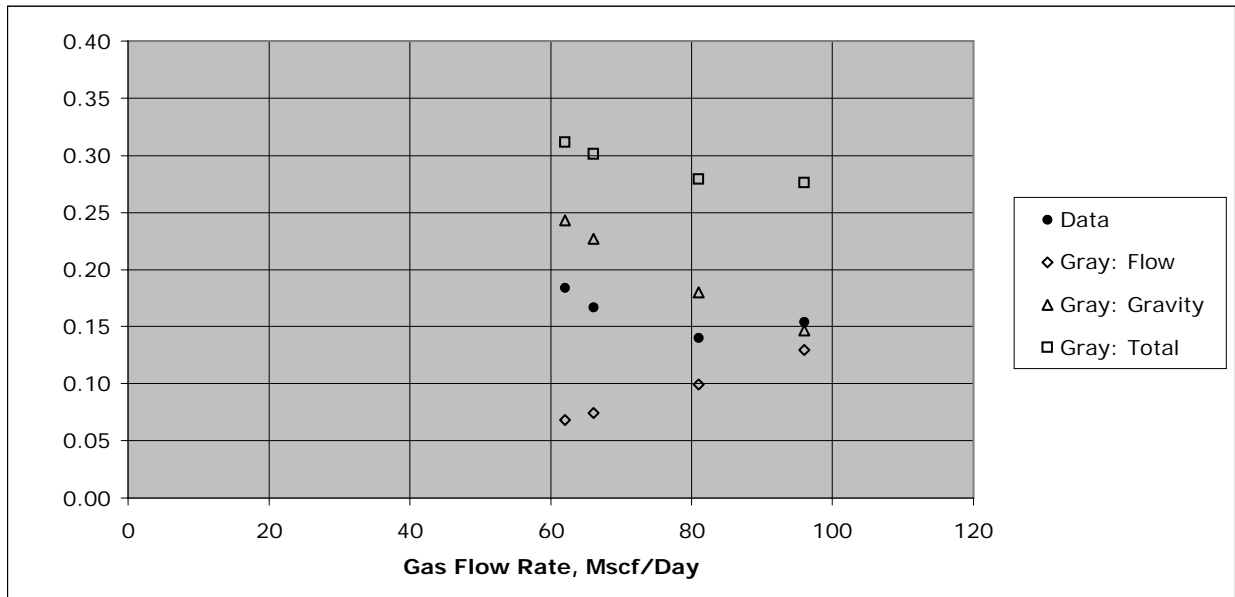


Figure 16. Comparison of measured pressure drops and the Gray correlation for water (without surfactant) flowing at 220 ml/min (2 bbl/day).

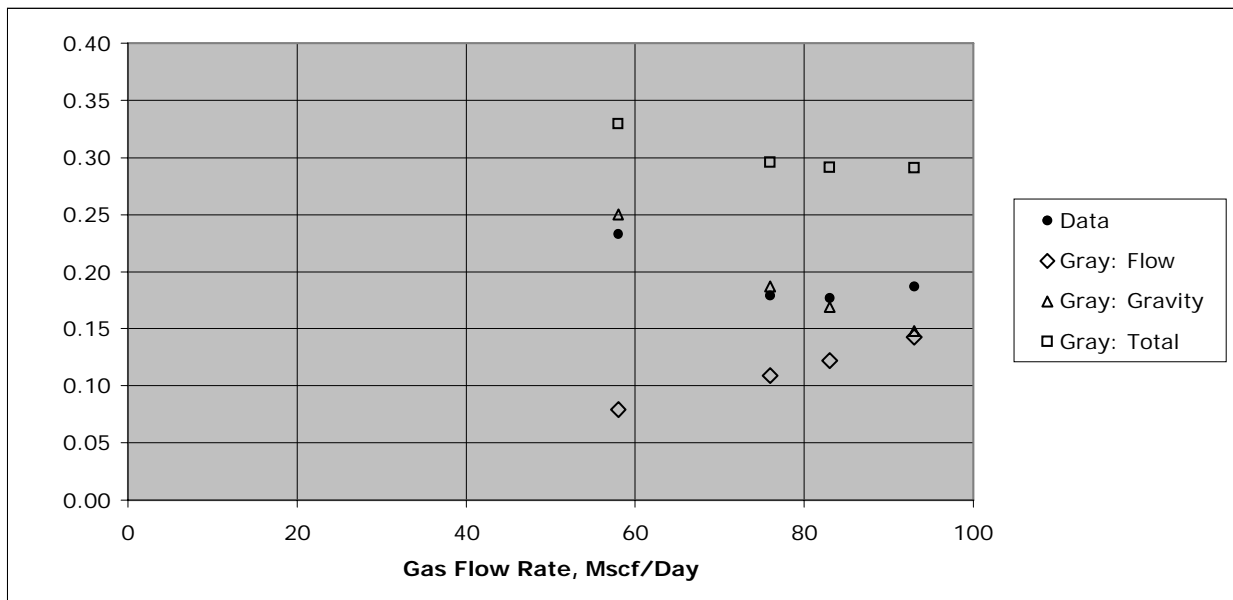


Figure 17. Comparison of measured pressure drops and the Gray correlation for water (without surfactant) flowing at 440 ml/min (4 bbl/day).

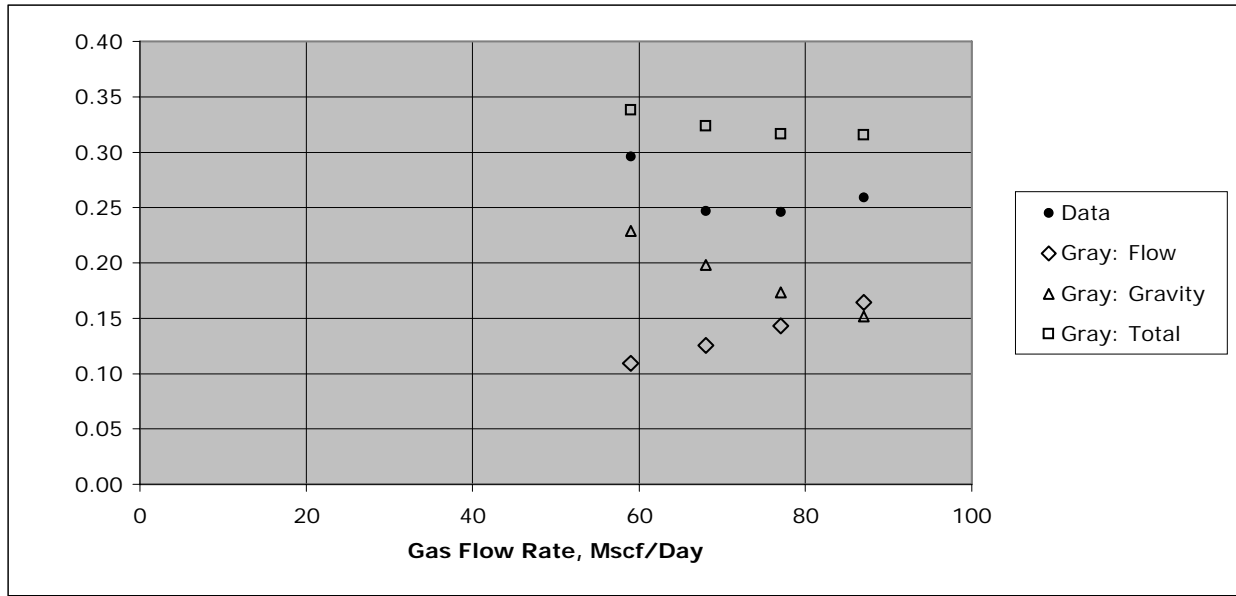


Figure 18. Comparison of measured pressure drops and the Gray correlation for water (without surfactant) flowing at 880 ml/min (8 bbl/day).

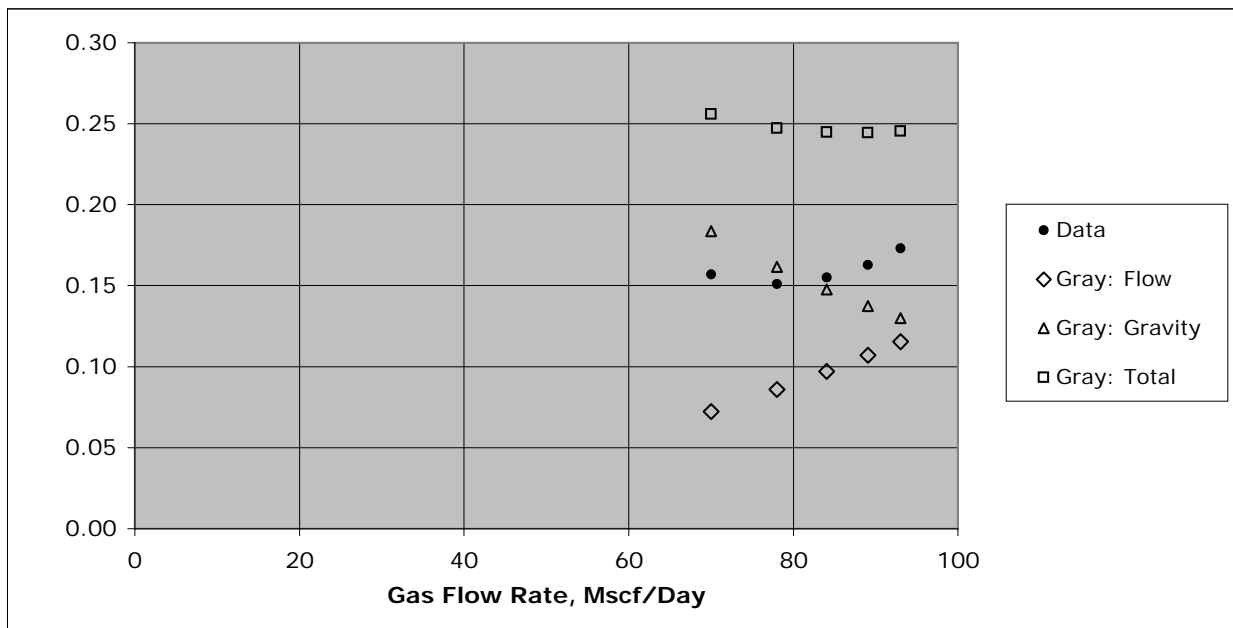


Figure 19. Comparison of measured pressure drops and the Gray correlation for water (with surfactant) flowing at 220 ml/min (2 bbl/day).

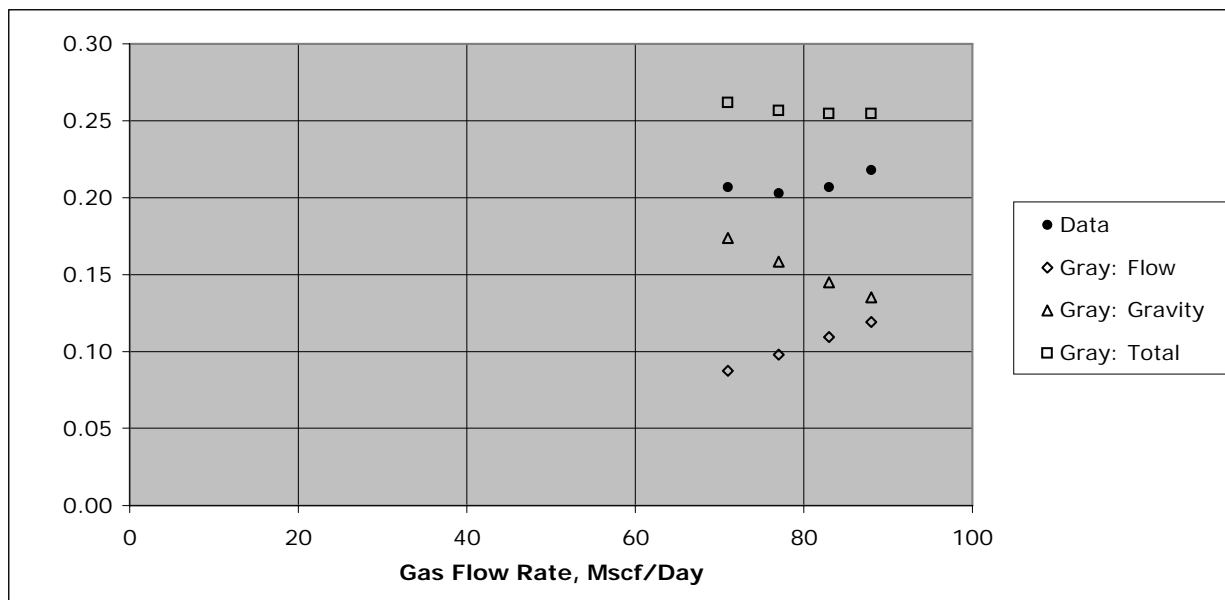


Figure 20. Comparison of measured pressure drops and the Gray correlation for water (without surfactant) flowing at 440 ml/min (4 bbl/day).

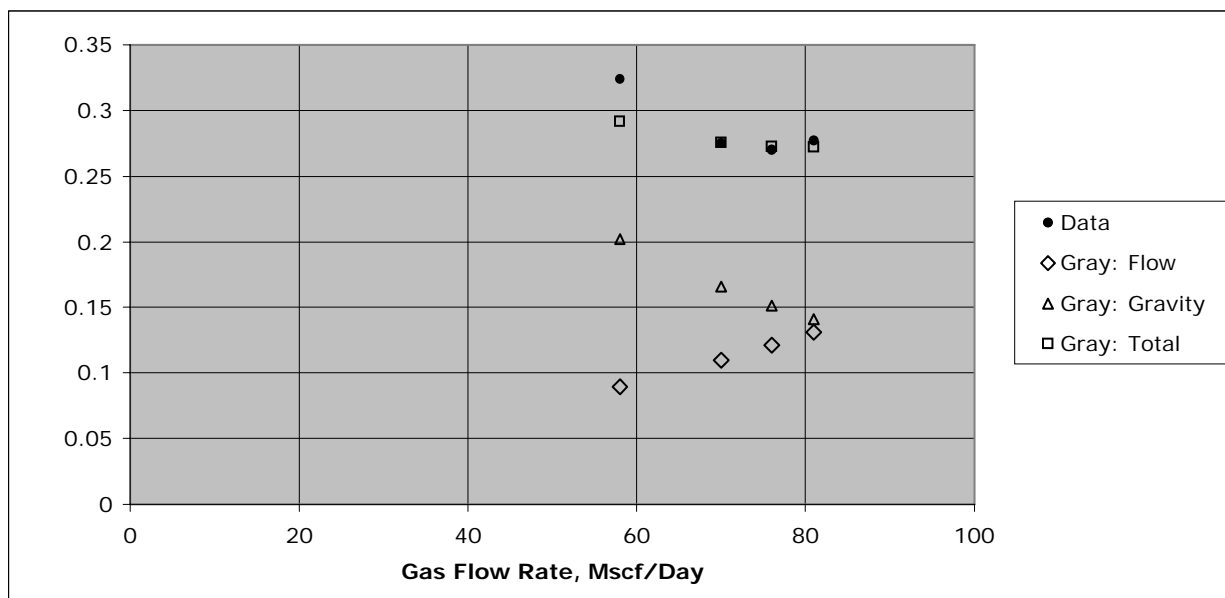


Figure 21. Comparison of measured pressure drops and the Gray correlation for water (without surfactant) flowing at 880 ml/min (8 bbl/day).

The results above are encouraging, but measurements with foam-inducing surfactants at lower gas flow rates are needed.

Task 3: New Correlation. The results discussed in the previous section show that the Duns-Ros correlation works better for describing pressure drop with surfactant than with plain

water. The Gray correlation may also be adequate for estimating pressure drop when water rates are above 4 bbl/day.

Task 4: Liquid-Lifting Short Course. Two short courses (one in March 2005 and one in October 2005) were held with about 10 participants in each course. In addition, arrangements were made to provide a short course for the 2006 Gas Well De-Liquification Workshop to be held in Denver on February 27 to March 1 of 2006.

The short courses delivered in March and October were organized for engineers of Marathon Oil Company. Each course lasted one and one-half days. A portion of the time (3 to 4 hours) was allotted to general and specific discussion of liquid-lifting issues with a lot of participation by attendees. The remainder of the time was devoted to the following demonstrations with the flow loop:

- Flow regimes (Bubble, Slug, Churn, Annular)
- Loading-up of well with water and termination of gas flow
- Breakup of water droplets (critical Weber number)
- Critical flow rates (Compare flow loop observations with estimates from THD correlation)
- Tubing-casing junction
- Effect of tubing couplings and tubing inserts
- Vortex tools
- Plungers
- Annular flow
- Foam flow

The time for each demonstration varied from 30 minutes to 1 hour. The demonstrations inspired a lot of discussion.

I anticipate presenting many more short courses in 2006.

Task 5: Final Development and Testing of Mist Device. The plan for this device specifies two main parts: an electrical power converter to provide the driving voltage for the ultrasonic device, and the ultrasonic device itself. The first part was completed, but we stumbled on the second part. I have arranged for funding from a private source to pay for completion of the device in 2006.

Conclusions

1. Critical flow rate was measured in a flow loop with two approaches: constant-rate and fixed-charge.
2. For water without surfactant added, the critical flow rate from the constant-rate tests varied with liquid flow rate.
3. For water with surfactant, the critical flow rate from the constant-rate tests varied from above to below the critical rate for water without surfactant as the liquid flow rate increased from 1 to 8 bbl/day.
4. Critical rate from the fixed-charge method is indicated by the height of a “stagnant” annular film. The 40-foot-tall flow loop was not sufficient to establish the asymptote for tests with water without surfactant. With surfactant, the critical flow rate was more apparent with increasing volume of the charged liquid.
5. The critical rate for water with surfactant as indicated by the fixed-charge method was one-third to one-half of the critical rate for water without surfactant.
6. The relationship between pressure drop and flow rate was measured from just below to somewhat above the critical flow rate as indicated by constant-rate tests in the flow loop.
7. Above the critical flow rate (as indicated by the constant-rate tests) the pressure drop for foam flow was higher than for water without surfactant.
8. The Duns-Ros and the Gray correlation over-predict the pressure drop for water without surfactant. With surfactant, both correlations performed better. The agreement improved with increasing liquid flow rate.

Acknowledgements

Of course, the financial support from the Stripper Well Consortium is very much appreciated. Without it, none of this work could have been completed. In addition, I would like to recognize contributions of students: Eric Giriya (an MS student who graduated in May 2006), Luke Riggins (a BS student who also graduated in May 2006), Garrett Elsener and Jed Wagner (both are BS students who will graduate in the next year). I also want to acknowledge support from Dr. Sunder Ramachandran of Baker Petrolite, Mr. Rob Lestz of Chevron, and Mr. Rob Sutton of Marathon Oil Company.

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